Technical Report No. 5-32421
Contract No. DAAH01-89-D-0134
Delivery Order No. 11

1

Engineering Support for Inertial Measurement Unit Development

December, 1990

Final Technical Report for Period
7 June 1990 to 15 December 1990

Prepared by

K. Walker
W. Engelke

Research Institute
University of Alabama in Huntsville
Huntsville, AL 35899

Prepared for:

System Engineering & Production Directorate
U. S. Army Missile Command
Manufacturing Methods & Technology
Redstone Arsenal, AL 35989

Attn: Mr. R. Hubbard
AMSMI-RD-SE-MT

unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION unclassified	1b. RESTRICTIVE MARKINGS none
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Distribution A (unlimited).
2b. DECLASSIFICATION DOWNGRADING SCEHDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) 5-32421	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION UAH Research Institute 6b. OFFICE SYMBOL (If applicable) E47	7a. NAME OF MONITORING ORGANIZATION Commander, US Army MICOM Engineering Directorate
6c. ADDRESS (City, State and ZIP Code) University of Alabama in Huntsville, Huntsville AL 35899	7b. ADDRESS (City, State and ZIP Code) ATTN: AMSMI-RD-SE-MT
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 6b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAH01-89-D-0134, D.O. 11
8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)* Engineering Support for Inertial Measurement Unit Development (unclassified)

12. PERSONAL AUTHOR(S) W. Engelke, K. Walker

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	From 06/90 To 12/90	90, Dec, 15	

16. SUPPLEMENTARY NOTATION

17. COSATI CODES		
FIELD	GROUP	SUBGROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Inertial measurement, robotics, accelerometer, gyroscope

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

This report documents engineering support provided to assist with the development of inertial measurement units for robots. It discusses the development, operation, and characteristics of an accelerometer test bed and some specifications for a gyroscope based system.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT [x] UNCLASSIFIED/UNLIMITED [ ] SAME AS RPT. [ ] DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION
22a. NAME OF RESPONSIBLE INDIVIDUAL R. Hubbard	22b. TELEPHONE (Include Area Code) (205)-842-7651 22c. OFFICE SYMBOL AMSMI-RD-SE-MT

Preface

This Technical Report was prepared by the staff of the Research Institute, The University of Alabama in Huntsville. It documents the research performed under contract DAAH01-89-D-0134, Delivery Order 11. Mr. William D. Engelke was the Principal Investigator. Technical work was accomplished by Messrs. Randolph Bolton and Kenneth Walker of the University of Alabama in Huntsville. Mr. Randy Hubbard of the System Engineering and Production Directorate was the technical monitor, with additional technical input from Mr. Martin Harris.

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as and official Department of the Army position, policy, or decision unless so designated by other official documentation.

Except as provided by the Contract Data Requirements List DD form 1423, hereof, the distribution of any contract report in any stage of development or completion is prohibited without the approval of the Contracting Officer.

Prepared for: U. S. Army Missile Command
Commander
Redstone Arsenal, AL 35898-5280

I have reviewed this report, dated 15 December 1990, and it contains no classified information.

W. D. Engelke
Principal Investigator

Approved:

Terry N. Long
Associate Director, UAH Research Institute

Table of Contents

I. INTRODUCTION....1
- A. Background....1
- B. Summary of Effort....3

II. IMU REQUIREMENTS....5
- A. Introduction....5
- B. Reasonable Robot Motions....5

III. TEST BED SPECIFICATION....9
- A. Introduction....9
- B. Linear Tables and Motors....11
- C. Data Acquisition System....12
- D. Computer and Software....12
- E. Accelerometers....13

IV. TEST PLAN....13
- A. Test bed Operation....13
- B. Test Plan for Linear Inertial Devices....13

V. CONCLUSIONS AND RECOMMENDATIONS....14
- A. Introduction....14
- B. Conclusions....15
- C. Future Directions....16

VI. REFERENCES....16

List of Figures

Figure 1. Typical joint controlled robot 1
Figure 2. Joint-sensor based manipulator control..2
Figure 3. Inertial sensor based manipulator control.......................................2
Figure 4. Typical motion calculation...6
Figure 5. Typical acceleration profile..8
Figure 6. Current IMU test bed 11

List of Tables

Table 1. DAAH01-87-D-0182 IMU system specification 6
Table 2. Typical robot motions...7

I. INTRODUCTION

A. Background

Typical robotic end effectors are positioned using feedback from encoders located in or at the manipulator joints (Figure 1). Joint angles are measured and kinematics are used to determine the position of the effector. Since the link sizes are precisely known, joint angle measurement provides reasonable accuracy in determining effector positioning; however, this accuracy is not sufficient for many robotic positioning tasks. If the manipulator is heavily loaded, static and dynamic deflection of the links may allow false indication of effector position (Figure 2), and for work requiring accurate positioning, this error can be disastrous.

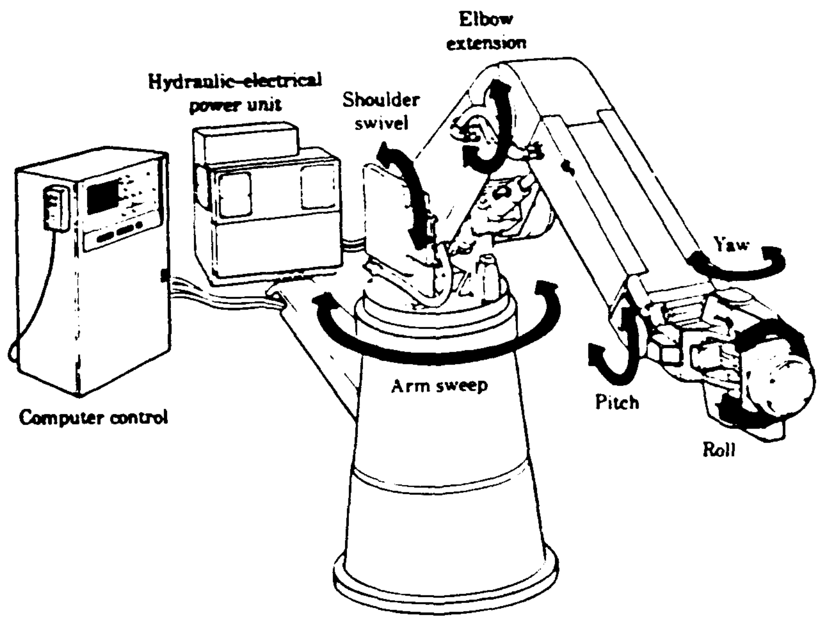


Figure 1. Typical joint-controlled robot. [4]

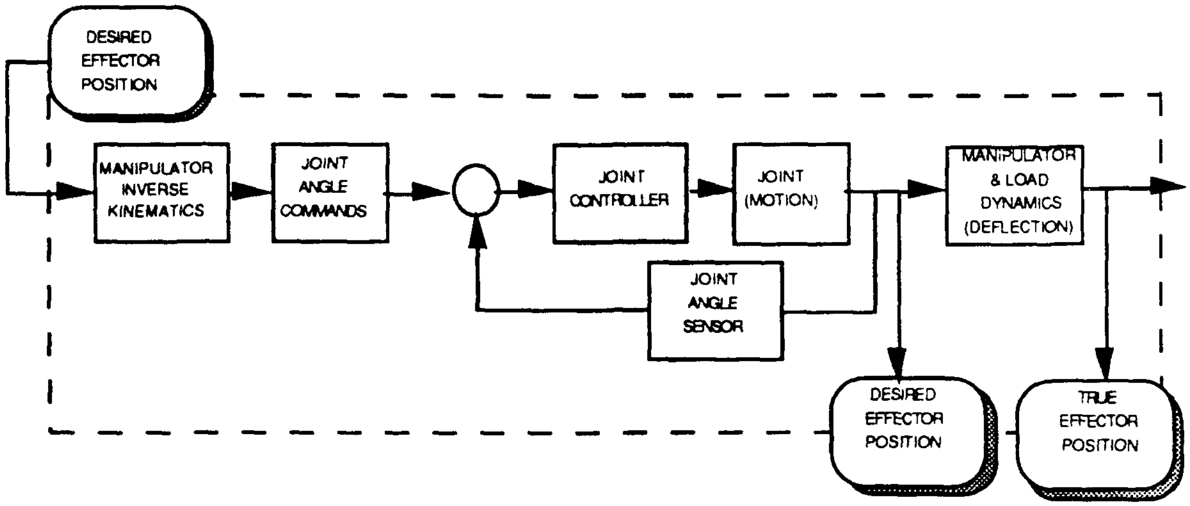


Figure 2. Joint-sensor based manipulator control.

It is desirable, then, to add a feedback mechanism to robot manipulators to give a truer indication of real effector position and allow tighter, more precise manipulator control (Figure 3). Proximity sensors, sonar and radar, and vision systems have been used with some success, but positioning has still not advanced sufficiently to allow a robot to precisely position a load approaching its maximum mechanical payload capacity. Since systems can not yet compensate for manipulator deflection under unknown loads, manipulators must be structurally over designed (at great expense) and payload capacity must be limited to loads which can be carried with minimal deflection. A more accurate method of measuring absolute end effector position is needed.

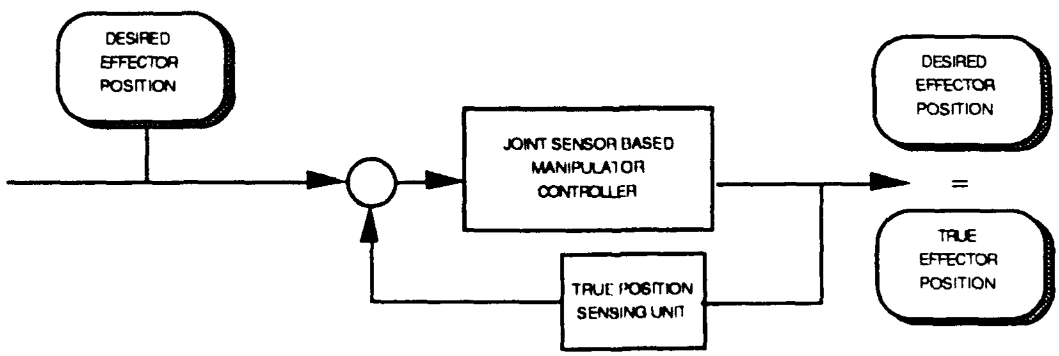


Figure 3. Inertial sensor based manipulator control.

One method which may prove adequate to monitor end effector position is the use of inertial sensors. Inertial sensors such as gyroscopes and accelerometers can be used to sense location within an inertial frame. If the accuracy and reliability of this sensing can be developed/demonstrated to be sufficient to provide precise end effector position readouts, then controllers can be designed to correct for position errors in real time, making manipulators more robust and manipulator control more reliable.

The U.S. Army MICOM is interested in analyzing inertial sensors to determine the accuracy, etc. required for a robotic inertial measurement system. If such devices are available and can be located, then MICOM desires to develop an Inertial Measurement Unit (IMU) which can be integrated into a robotic manipulator system. This task was conducted to assist the development of a test bed for analyzing and evaluating inertial sensors.

B. Summary of Effort

This report summarizes effort and engineering capabilities provided by the UAH Research Institute in support of MICOM's ongoing effort to develop a test bed for testing inertial devices. Results of the testing will be used toward the development of Inertial Measurement Units (IMUs) for robotic systems. Effort on the project is summarized below, along with a summary of task requirements from the Statement of Work (SOW).

> **SOW:** *Provide engineering capabilities in the areas of mechanical design, dynamic analysis, computer control and data acquisition, and sensor integration techniques.*
>
> RI personnel provided support in selecting additional hardware and software necessary to develop an operable configuration of the existing test bed. Existing hardware was evaluated and modifications were made as appropriate. Analysis was conducted to establish the requirements of a real robotic system. Further analysis was conducted to determine whether the test bed approximates a real robotic system. Software was written/modified to facilitate and simplify data acquisition and analysis. Interfaces with pre-selected accelerometers were established. Limited research into additional sensor technology (gyroscopes) was conducted.

SOW: *Set up and integrate the test platform initially and for each inertial device to be tested.*

An operable configuration of the test bed was developed. Testing is still crude at this point but can be laboriously conducted without further modification to the system. No formal testing of inertial devices has yet occurred.

SOW: *Develop an IMU test bed platform which will be utilized to test and evaluate inertial devices.*

The current system as developed is capable only of testing accelerometers, and that testing capability is still somewhat simplistic. A detailed explanation of the current system and its capabilities is contained in this report. The test bed should be expanded to include other inertial sensors. Some suggestions for such further development are included in the "Conclusions and Recommendations" section.

SOW: *Integrate the IMU test bed with an off the shelf data acquisition system.*

A MetraByte DAS-20 12 bit DAS was selected and purchased by MICOM personnel. Software supplied with the DAS was modified to suit the specific needs of the IMU test bed.

SOW: *Document the interfaces necessary to connect each inertial test device to the computer data acquisition system.*

Additional equipment required for operating each of the accelerometers was purchased along with the accelerometers. Consequently, interfaces to the test bed are completed by simply attaching each unit's signal and ground wires to the channel 0 and analog ground inputs of the DAS-20 data acquisition board. All necessary schematics were supplied by the accelerometer manufacturers and are in the possession of appropriate MICOM personnel.

SOW: *Prepare a program plan and milestone chart defining in detail a schedule for all planned work tasks. Prepare a monthly program progress report. Provide a monthly performance and cost report. Provide a final technical report.*

A program plan and a milestone chart were prepared and submitted at the beginning of the task. Monthly reports were submitted through contractual channels at appropriate intervals. This document is to serve as the final project report.

OTHER: *Other desired activities included a survey of gyroscope technology and details of a system of testing gyroscopes for inertial measurement use.*

Commercial inquiries were made and gyroscope information was acquired. While no formal analysis of the gyroscope data has yet occurred, most mechanical gyros seem to be well outside the weight restrictions for a robotic IMU device. Available gyroscope data has been transferred to MICOM personnel to be used in any follow-on IMU work.

The remainder of this report summarizes the technical analysis conducted and data gathered in support of the IMU test bed development.

II. IMU REQUIREMENTS

A. Introduction

The direct purpose of an IMU test bed at this time is to select inertial measurement devices for precisely monitoring and controlling robot motions. Selection of inertial devices and development of the test bed itself must be based upon reasonable standard robot motions -- but what is a reasonable robot motion? What linear and angular accelerations, velocities, and displacements can be expected in a robotic system? What accuracies are required?

B. Reasonable Robot Motions

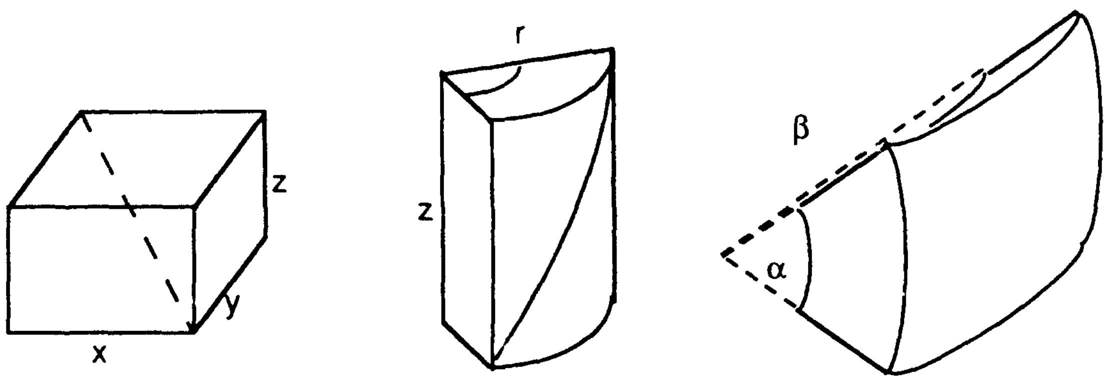
Previous research in IMU development (see MICOM contract DAAH01-87-D-0182) was based on the system specification shown in Table 1. The previous system consequently required 22 data bits per data point to represent the required acceleration resolution and range, and much of the researcher's effort was lost in developing data acquisition schemes to cope with this specification. Even at <1 G acceleration, a 1 μG resolution exceeds the capabilities of all but the most expensive A/D converters—not to mention the capabilities of controllers which might eventually be used to process inertial data and generate robotic control signals. Perhaps it is wise, therefore, to reexamine the specification for a reasonable robot motion.

Table 1. DAAH01-87-D-0182 IMU System Specification

Maximum acceleration magnitude:	±2 G
Position accuracy desired:	100 micron or 0.004 in
Acceleration resolution:	1 micro G (μG)
Control sampling rate:	100 Hz

Robot end effector speeds of up to 12 m/s [472 in/s] and accelerations of over 5 G [1929 in/s/s] are possible in the laboratory, but reports describe the motions a "extremely fast." [1]. More general robot motions (Table 2) are derived from common robot data recorded in literature [5]. As shown in Table 2, typical robot velocities are on the order of 20-50 in/s, with distances traveled on the order of 50-250 in. (Distances are calculated using the equations in Figure 4 and data from [5]). By assuming a reasonable motion profile (Figure 5), typical effector velocities and accelerations can be determined from the distances.

Cartesian* (X-Y-Z)	*Cylindrical**	*Spherical**
$D=\sqrt{x^2+y^2+z^2}$	$D=\sqrt{\left(2\pi r\frac{\alpha}{360°}\right)^2+z^2}$	$D=\sqrt{\left(2\pi r\frac{\alpha}{360°}\right)^2+\left(2\pi r\frac{\beta}{360°}\right)^2}$



(a) (b) (c)

*(Typical distance = D/2; α and β are in degrees)

Figure 4. Typical motion calculation

Table 2. Typical Robot Motions [5]

Payload (LBS)	Description	Repeatability (± inches)	Typical Travel* (inches)	Typical Speed (in/sec)	Typical Accel ** (in/sec2)	Acceleration in G's
1	Anthropomorphic, electric stepper motor, 3 axis	0.03	9	7	22	0.06
2.2	Cylindrical, pneumatic, 3 axis	0.001	22	40	291	0.75
2.2	Anthropomorphic, electric servo, 4 axis	0.002	44	39	138	0.36
5	Spherical, pneumatic, 5 axis	0.005	59	20	27	0.07
5	Spherical, electric serco, 5 axis	0.004	64	55	189	0.49
6	Anthropomorphic, electric servo, 6 axis	0.04	95	20	17	0.04
11	Anthropomorphic, electric servo, 6 axis	0.002	66	20	24	0.06
14	X-Y-Z, electric servo, 12 axis	0.001	53	30	68	0.18
16	X-Y-Z, hydraulic servo, 6 axis	0.008	58	40	110	0.29
22	Anthropomorphic, electric servo, 6 axis	0.006	185	40	35	0.09
35	X-Y-Z, electric servo, 5 axis	0.008	133	60	108	0.28
50	Anthropomorphic, pneumatic servo, 5 axis	0.4	245	80	104	0.27
50	Cylindrual, hydraulic servo, 4 axis	0.05	118	30	31	0.08
50	Spherical, hydraulic servo, 5 axis	0.05	151	30	24	0.06
70	Anthropomorphic, electric servo, 6 axis	0.01	267	25	9	0.02
100	Spherical, 3 to 5 axis	0.008	99	15	9	0.02
100	X-Y-Z, electric servo, 6 axis	0.004	124	15	7	0.02
100	Anthropomorphic, hydraulic servo, 7 axis	0.05	243	50	41	0.11
150	Anthropomorphic, hydraulic servo, 6 axis	0.01	263	30	14	0.04
175	X-Y-Z, hydraulic servo, 5 axis	0.008	72	30	50	0.13
225	Anthropomorphic, hydraulic servo, 6 axis	0.05	283	35	17	0.04
250	Cylindraul, hydraulic servo, 7 axis	0.05	118	36	44	0.11
300	Spherical, hydraulic servo, 6 axis	0.05	134	20	11	0.03
450	Spherical, hydraulic servo, 6 axis	0.08	207	20	8	0.02
600	Cylindrical, hydraulic servo, 6 axis	0.05	117	20	14	0.04
2000	Cylindrical, hydraulic servo, 6 axis	0.08	117	15	8	0.02
N/A	Spherical, hydraulic servo, 5 axis	0.06	44	30	82	0.22
N/A	X-Y-Z, electric servo	0.01	133	300	2707	7.02
N/A	Anthropomorphic, hydraulic servo	0.032	99	36	52	0.14

* Typical motion assumed to be one half of maximum motion. Maximum motion calculated as follows from operating envelope data listed in [5].

X-Y-Z: Maximum corner to corner distance, e.g. Figure 4 (a).
Cylindrical: Corner to corner distance across cylinder face, e.g. Figure 4 (b).
Spherical: Corner to corner distance across largest accessible spherical region, e.g. Figure 4 (c).
Anthropomorphic: One of above coordinate systems chosen to match operating envelope data supplied.

** Typical acceleration calculated using the following assumptions and the motion profile shown in Figure 5.

Distance X/4 is moved in time S/3 (acceleration),
Distance X/2 is moved in time S/3 (run),
Distance X/4 is moved in time S/3 (deceleration.
Constant acceleration for 1/3 of total motion,
Constant velocity for 1/3 of total motion,
Constant deceleration for 1/3 of total motion.

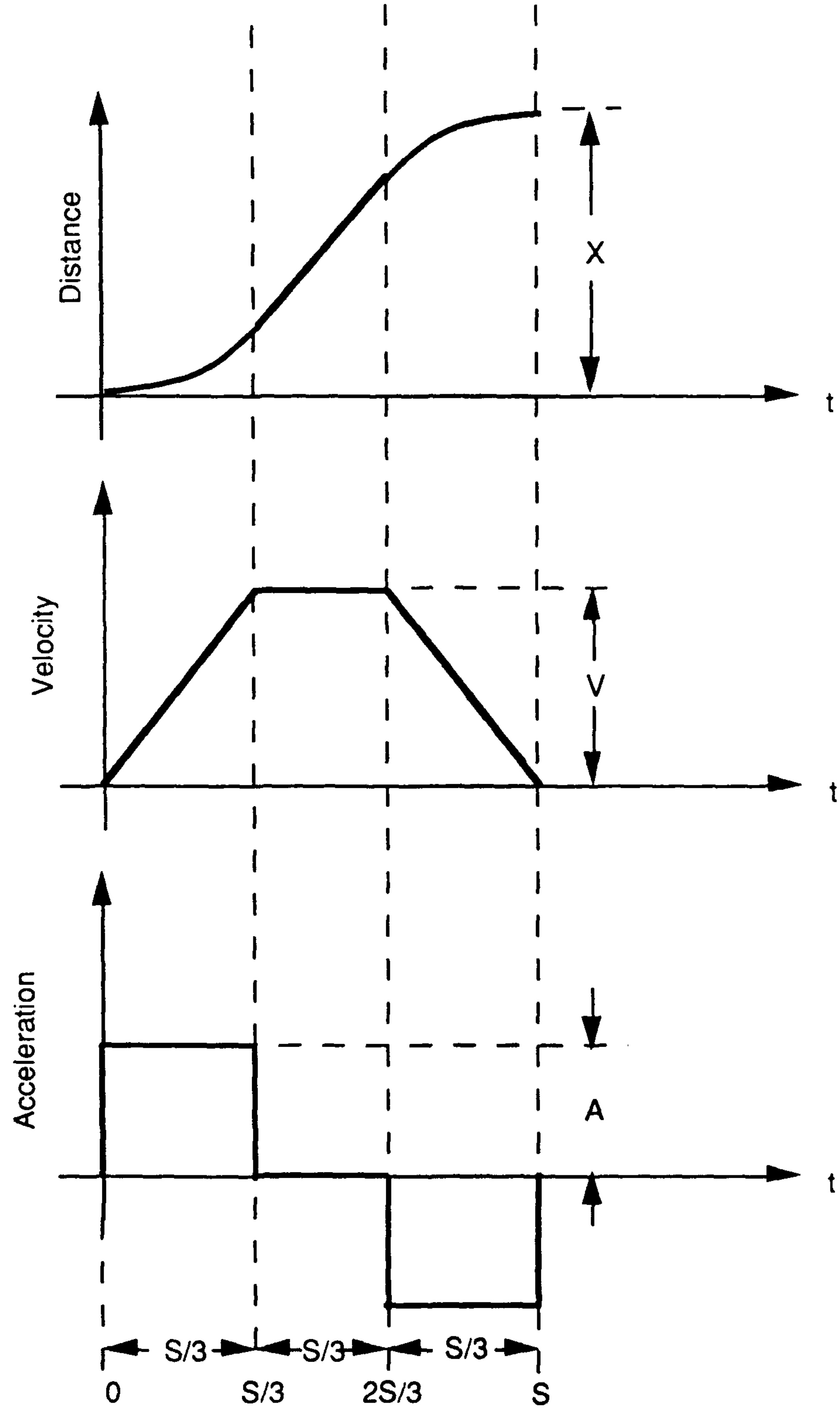


Figure 5. Typical acceleration profile

For piecewise-constant acceleration, the following motion equation is standard.

$$X = X_0 + V_0 t + \frac{1}{2}At^2$$

For the acceleration portion of the motion described in Figure 5, X_0 and V_0 are both zero, so the equation reduces to:

$$X = \frac{1}{2}At^2 \quad \text{or} \quad A = \frac{2X}{t^2}$$

Substituting the appropriate values from Figure 5 then yields an equation for acceleration in terms of the distance traveled at constant A (S/3).

$$A = \frac{2X}{t^2} = \frac{2\left(\frac{X}{4}\right)}{\left(\frac{S}{3}\right)^2} = \frac{4.5X}{S^2}$$

Likewise, substituting values into the standard velocity equation at time S/3 ("A" still constant) yields:

$$V = At = \frac{4.5S}{S^2} \times \frac{S}{3} = \frac{1.5X}{S} \quad \text{and} \quad S = \frac{1.5X}{V}$$

Combining these two equations yields an equation for acceleration in terms of velocity and distance traveled, both of which are known from the tabular data in [5].

$$A = \frac{4.5X}{\left(\frac{1.5X}{V}\right)^2} = \frac{2V^2}{X}$$

This final form of the acceleration equation was used to calculate the acceleration values in Table 2.

III. TEST BED SPECIFICATION

A. Introduction

As shown in figure 3, the current IMU test bed is composed of 6 major elements:

1) Inertial Unit Under Test — An accelerometer which has been mounted to the test bed such that the sensitive axis to be tested lies parallel to the axis of motion of the motion table.

2) Linear Table — A high precision, leadscrew-driven X-axis table which is isolated from background motion noise by a large aluminum plate and a sheet of neoprene.

3) Data Acquisition System (DAS) — A MetraByte DAS-20 successive approximation A/D converter which provides 12 bits of parallel digital output at up to 100 kHz sampling rate.

4) Control Computer — An i386DX-20 based machine (with 387DX-20 math coprocessor) which is used for processing and storing data, displaying graphs, generating motor control parameters, and controlling data acquisition.

5) Test bed Software — A set of Commercial-Off-The-Shelf (COTS) and vendor supplied software integrated and/or modified for IMU laboratory use. The current software includes:
    a. motor control -- Compumotor, GWBASIC, ProComm
    b. data acquisition -- DAS-20 software (with modifications)
    c. data processing and display -- MathCAD (with batch and plot routines)

6) Compumotor, Indexer/Controller, and Absolute Encoder — A 12800 step/revolution microstepper motor with absolute and optical position encoder readouts.

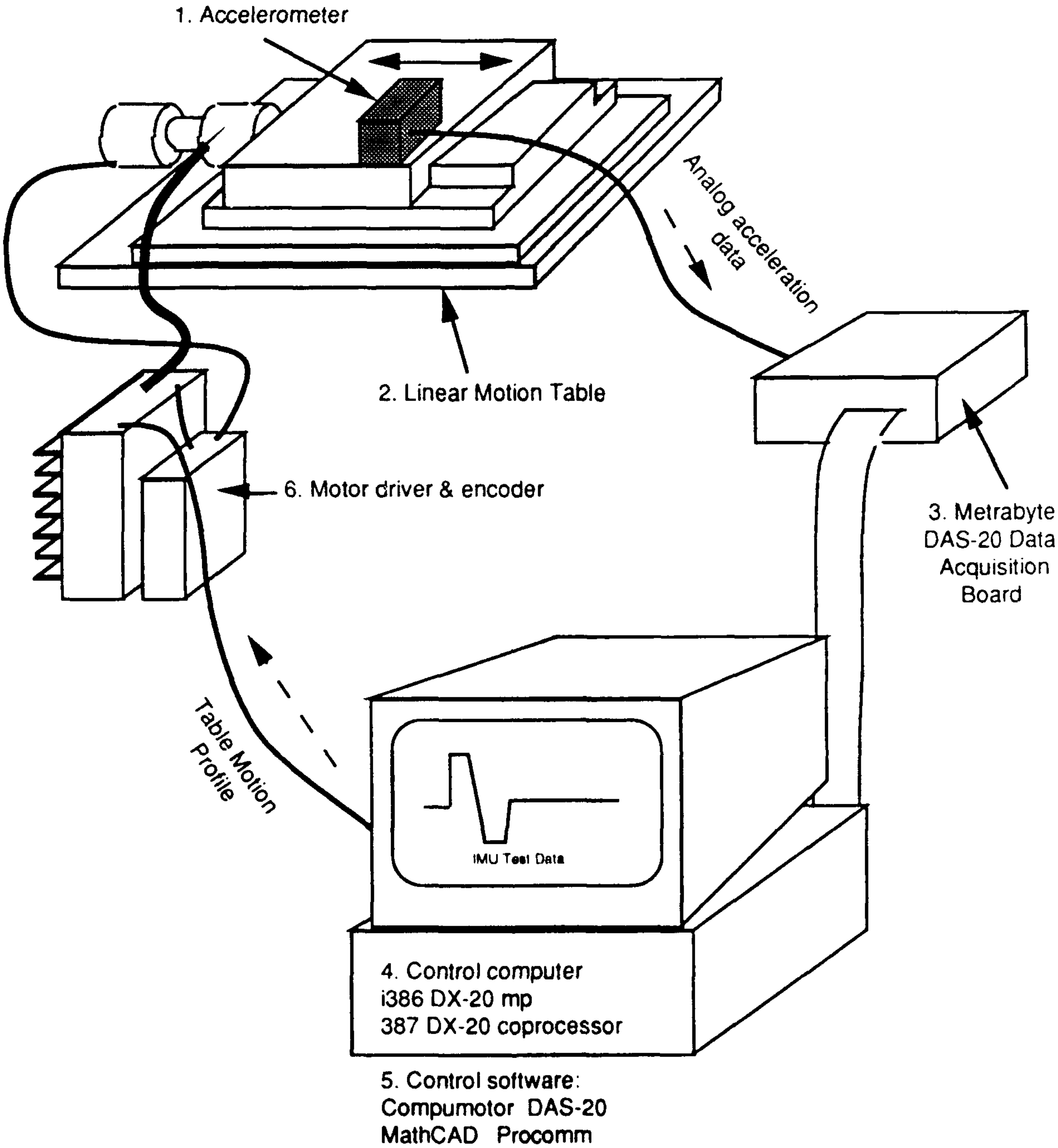


Figure 6. Current IMU test bed

Some details of test bed element selection are given in the following sections.

B. Linear Tables and Motors

Leadscrew-driven linear motion tables were on hand from another project and were thought to be adequate for test bed use. As no technical data was available for the motors currently attached to the tables, new motors were selected. Compumotor 12800 step/revolution microstepper motors were added to create precise, computer controllable automated linear tables.

C. Data Acquisition System

A 12 bit MetraByte A/D converter was selected for the project because it was inexpensive and readily available. Can the board be expected to supply a reasonable amount of data to enable accurate calculations? Given a reasonable acceleration profile, what must the DAS sampling rate be to insure adequate data?

D. Computer and Software

An IBM PC compatible i386DX-20 based personal computer was chosen as the control computer for the test bed. The machine is outfitted with the corresponding math coprocessor (387DX-20) and a MetraByte DAS-20 data acquisition board. The data acquisition board contains 64K of Random Access Memory in addition to the computers own RAM.

The test bed makes use of the following software for processing and storing data, displaying graphs, generating motor control parameters, and controlling data acquisition:

1) Compumotor motor control routines written in GWBASIC — Used to download to the motor controller a prescribed motion profile, which is then executed by the controller. The controller begins execution of the motion profile when a "G" (go) command is received. This allows a motion profile to be generated as a file and then downloaded to the controller with a standard communications package such as ProComm. Both methods have been successfully used, but because of their simplicity, the BASIC routines are preferred at this time.

2) DAS-20 software supplied by MetraByte — Used to configure the DAS-20 data acquisition board to gather data from a single channel, using differential input, at unity

gain (or higher gain if this gain proves insufficient during testing). The software was modified to execute only those DAS-20 options necessary for IMU data acquisition.

3) MathCAD — Used to plot acceleration data after data acquisition is complete. Macros were written to facilitate display of plots in the appropriate ranges of values expected during testing. This commercial package should also be able to perform integration of the acceleration data to obtain distance information for statistical comparison.

E. Accelerometers

Six Accelerometers were initially selected for study. As of the writing of this report, all 6 have been acquired and are ready for testing to begin. The accelerometers are as follows:

Vibro-Meter	CE510M101
Entran	EGCS-A-2
ICSensors	3110-002
Valtronic	V-ACCESS
Kistler T.A.P.	8832
Kistler Triax	8692B5

V. TEST PLAN

A. Test bed Operation

The current test bed is operated as follows:

1) Connect the accelerometer to be tested to the data acquisition board.
2) Load motor control program using GWBASIC.
3) Execute DAS-20 software to configure data acquisition system.
4) Simultaneously trigger motor motion and data collection.
5) Save data to a file.
6) Plot or manually integrate the file using MathCAD.

B. Test Plan for Linear Inertial Devices

The following is a brief description of accelerometer testing to be performed using the test bed. Other tests may be added as they are developed.

1. Drift Measurement

a. Allow accelerometer to sit with power applied.

i. gather time and temperature data

ii. allow different specific lengths of time

b. Allow accelerometer to travel in one direction. Gather data after motion has stopped.

i. gather time, distance, and temperature data

ii. allow different specific lengths of time

ii. allow different specific acceleration profiles

2. Cross-Axis Sensitivity

allow accelerometer to travel in one direction 90 degrees to its sensing axis.

i. gather time, distance, and temperature data

ii. allow different specific lengths of time

ii. allow different specific acceleration profiles

3. Accelerometer Accuracy

a. Allow accelerometer to travel in one direction. Gather data during motion and after motion has stopped.

i. gather time, distance, and temperature data

ii. allow different specific lengths of time

ii. allow different specific acceleration profiles

iv. compare acceleration data from accelerometer (all data points) with known acceleration profile. Compare position as calculated from accelerometer output with reported position of the linear table. Investigate and explain the differences between 2 and 3.

b. Allow accelerometer to travel in two directions. Gather data during motion and after motion has stopped.

i. gather time, distance, and temperature data

ii. allow different specific lengths of time

ii. allow different specific acceleration profiles

iv. compare and contrast as in 3.a.iv

V. CONCLUSIONS AND RECOMMENDATIONS

A. Introduction

A small, lightweight, and accurate IMU should greatly improve robotic effector positioning, enabling new and more efficient use of robots in military and industry. In addition to end effector positioning, an IMU might be used to assist autonomous robot navigation or to provide more efficient ballistics guidance. A high accuracy IMU might be used in conjunction with Global Positioning System (GPS) technology to provide an electronic personal compass to show a troop's exact location on a map. A miniature IMU might even have medical applications, helping to locate blockages for surgical removal. The search for an efficient IMU, then, has merit and should be continued. The following sections explain how the search might be continued.

B. Conclusions

The IMU test bed is currently configured so that testing can be performed; however, testing using the current system would be tedious, and the results potentially useless. While the current system can execute a defined motion profile and gather and display acceleration data, control of the experiment is still almost completely manual and the system can not convert the acceleration data it acquires to distance data it can use. At minimum, the system must contain some sort of integration routine that will convert the acceleration output data to distance data. Also, to maintain any sort of consistency in testing, the system must be configured so that a single switch (hardware or software) triggers the motor controller and the data acquisition system. These two modifications would allow the existing system to be moderately functional (albeit somewhat clumsy), and accelerometer testing can begin. As an alternative, there are numerous other options which would further improve the existing IMU test bed for linear inertial devices.

First, further mathematical analysis should be conducted to determine the requirements which a real robotic system would place on an inertial device, whether linear or angular. This analysis can be used to determine desired variables to test and whether existing test bed hardware/software is adequate to use for those tests. Results of the analysis should be recorded as a formal specification of IMU requirements. If other desired uses for an IMU arise, these requirements can be analyzed and added to the IMU specification.

Next, the existing hardware should be evaluated against the formal IMU requirements to determine whether the hardware/software is adequate to perform the IMU testing procedures. If not, new hardware/software must be specified/developed to meet the needs of the test bed.

If possible, existing data storage methods should be revised so that integration of the acceleration may be performed in real time. This might be accomplished with the current hardware by configuring the DAS to operate in interrupt mode and having an interrupt service routine integrate and store data as it is read (rather than using DMA). If this method looks to be too slow, high precision op-amps (analysis must be conducted to determine the required accuracy) may be acquired and used to construct analog integrators which convert the acceleration input to velocity and then to distance. Either or both of these signals may then be digitally sampled for display and statistical analysis. It should be possible to simultaneously sample three channels to get the distance, velocity, and acceleration data all at the same time.

Additionally, a formal motor motion profile generator should be written so that with each test the motor will:

1) go to home position and verify
2) set absolute position away from zero
3) timer/loop to allow settling
4) wait for trigger
5) execute acceleration curve

C. Future Directions

Concurrent with the completion/modification of the test bed for linear inertial devices, there is substantial justification for modifying the system to include angular inertial devices as well. While typical spinning mechanical gyros are far too heavy for use on the end of a robotic end effector, many new gyroscope technologies are emerging. Ring laser gyros have revolutionized gyro research and promise to far surpass the accuracy of their mechanical cousins. Fiber-optic gyros under development have not yet achieved the accuracy of regular ring laser gyros, but they promise to be far lighter in weight than even the smallest commercially available mechanical gyros, and they have the advantage of laser accuracy. Also, while they may be some time away from the commercial market, current inertial device research includes micro-machine gyros, accelerometers, and hybrids that may eventually replace even the optical devices.

VI. REFERENCES

[1] Asada, Haruhiko, and Kamal Youcef-Toumi. *Direct Drive Robots: Theory and Practice.* Cambridge, Massachusetts: The MIT Press, 1987.

[2] Hung, James C. "Analysis and Software for the Development of an Inertially Aided Robot Manipulator: A Final Report Prepared for U.S. Army Missile Command under Contract DAAH01-87-D-0182." Huntsville, Alabama: Computer Science Corporation, 1989.

[3] Hung, James C., and Don N. Pittman. "Inertially Aided Robotics: Final Report." Huntsville, Alabama: System Dynamics International, Inc., Report No. H-90--1 for U.S. Army Missle Command Contract No. DAAH01-88-D-0057, 1989.

[4] Miller, Rex. *Fundamentals of Industrial Robots and Robotics.* Boston, Massachusetts: PWS-KENT Publishing Company, 1988.

[5] Zeldman, Maurice I. *What Every Engineer Should Know About Robots.* New York: Marcel Dekker, Inc., 1984